Lecture 20

5. RF Systems and Particle Acceleration

5.2 Accelerating RF Cavities

5.2.3 Standing wave cavities

5.2.4 The pillbox cavity

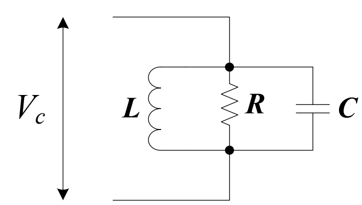
5.2.5 Higher-Order-Modes

5.2.6 SRF primer

Parallel circuit model

A resonant cavity can be modeled as a series of parallel circuits representing the cavity eigenmodes:

dissipated power $$P_c = \frac{V_c^2}{2R}$$



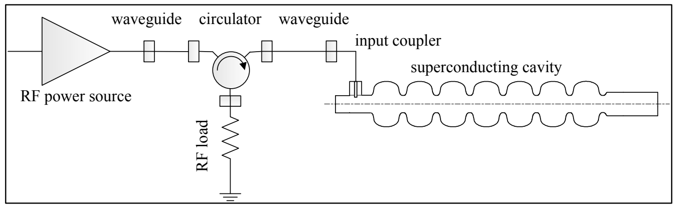
shunt impedance $$R_{sh} = 2R$$

quality factor $$Q_0 = \omega_0 CR = \frac{R}{\omega_0 L} = R\sqrt{\frac{C}{L}}$$

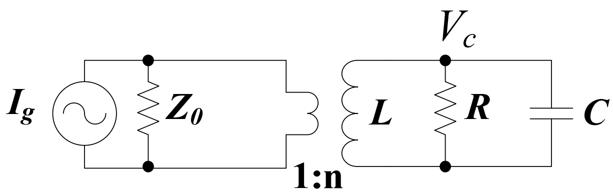
impedance $$Z = \frac{R}{1 + iQ\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)} \approx \frac{R}{1 + 2iQ\left(\frac{\omega - \omega_0}{\omega_0}\right)}$$

Connecting to a power source

- **Consider a cavity connected to an RF power source**



- **The input coupler can be modeled as an ideal transformer:**



External & loaded *Q* factors

- **If RF is turned off, stored energy will be dissipated now not only in *R*, but also in $Z_0 \cdot n^2$, thus**

$$P_{tot} = P_0 + P_{ext}$$

$$P_0 = P_c = \frac{V_c^2}{2R} = \frac{V_c^2}{R/Q \cdot Q_0} \qquad P_{ext} = \frac{V_c^2}{2Z_0 \cdot n^2} = \frac{V_c^2}{R/Q \cdot Q_{ext}}$$

- **Where we have defined an external quality factor associated with an input coupler. Such *Q* factors can be identified with all external ports on the cavity: input coupler, RF probe, HOM couplers, beam pipes, etc.**
- **Then the total power loss can be associated with the loaded *Q* factor, which is**

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext1}} + \frac{1}{Q_{ext2}} + \ldots$$

Coupling parameter β

- For each port a coupling parameter can be defined as

$$\beta \equiv \frac{Q_0}{Q_{ext}}$$

so

$$\frac{1}{Q_L} = \frac{1+\beta}{Q_0}$$

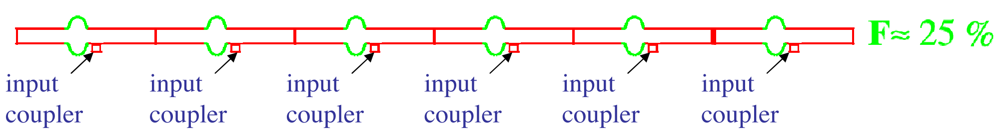
- It tells us how strongly the couplers interact with the cavity. Large β implies that the power leaking out of the coupler is large compared to the power dissipated in the cavity walls:

$$P_{ext} = \frac{V_c^2}{R/Q \cdot Q_{ext}} = \frac{V_c^2}{R/Q \cdot Q_0} \cdot \beta = \beta P_0$$

- And the total power from an RF power source is

$$P_{tot} = P_{forw} = (\beta + 1) P_0$$

Multicell Cavities: Why?



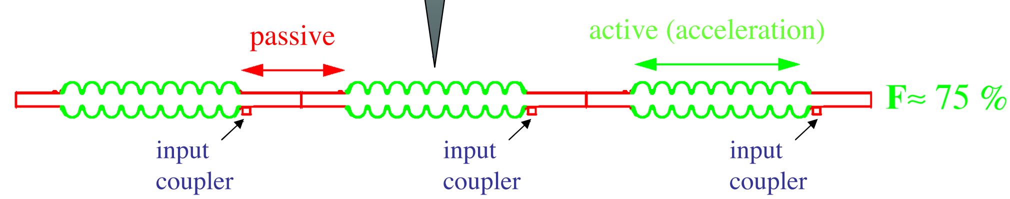
higher fill-factor:

$$F = \frac{\text{active length}}{\text{total length}}$$

⇒ *lower costs*

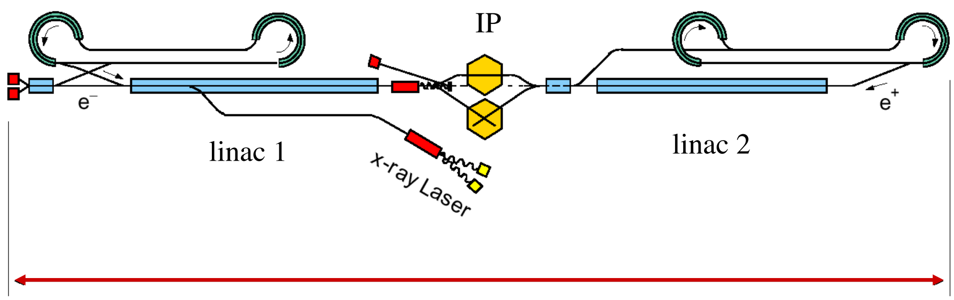
⇒ *better beam*

fewer
- input couplers
- waveguide elements
- RF control systems
- …



Multicell Cavities: Why?

Example: 500 GeV Linear Collider

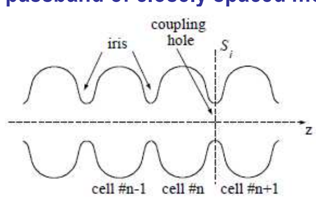


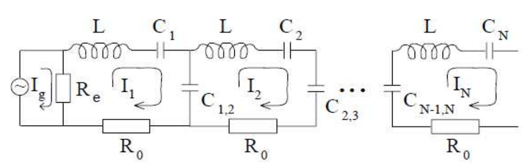
21,024 9-cell cavities: 27.8 km (17.3 miles)

189,216 1-cell cavities: 75.4 km (46.8 miles)

Multicell cavities

- **Several cells can be connected together to form a multicell cavity.**
- **Coupling of TM_{010} modes of the individual cells via the iris (primarily electric field) causes them to split into a passband of closely spaced modes equal in number to the number of cells.**

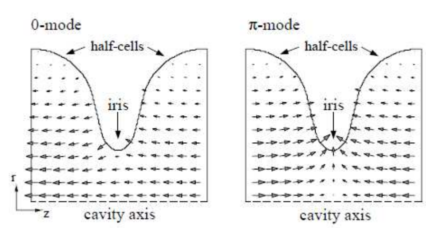




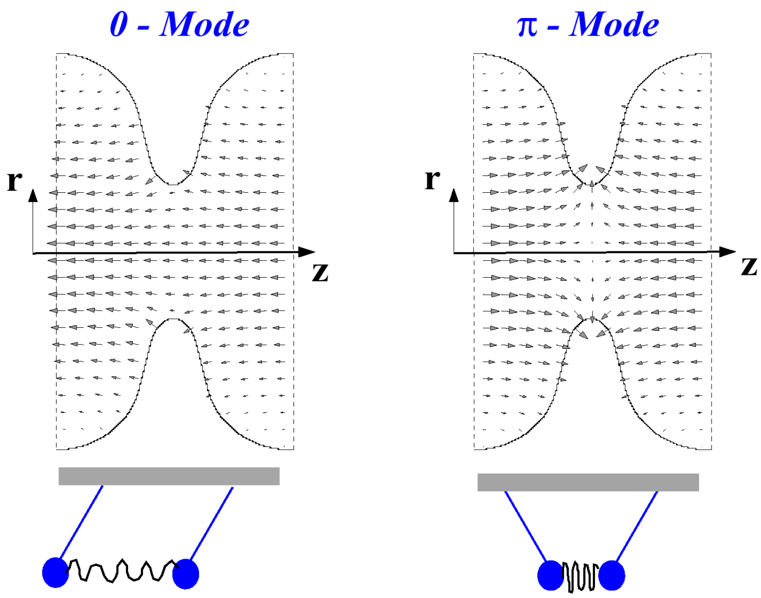
- **The width of the passband is determined by the strength of the cell-to-cell coupling *k* and the frequency of the *n*-th mode can be calculated from the dispersion formula**

$$\left(\frac{f_n}{f_0}\right)^2 = 1 + 2k\left[1 - \cos\left(\frac{n\pi}{N}\right)\right]$$

where *N* is the number of cells, *n = 1 … N* is the mode number.



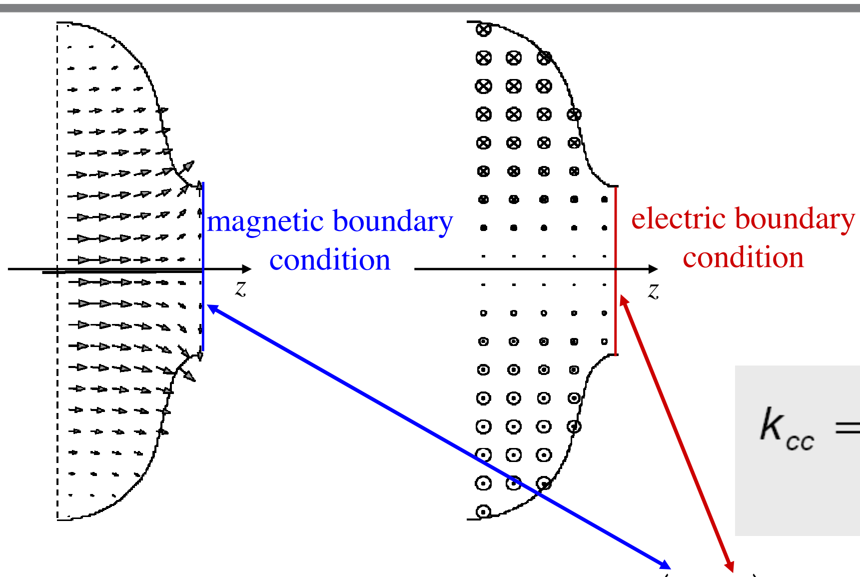
Two Coupled Cells: TM010 Modes



2 coupled cells ⟹ ***2 TM_{010} modes***

n coupled cells ⟹ ***n TM_{010} modes***

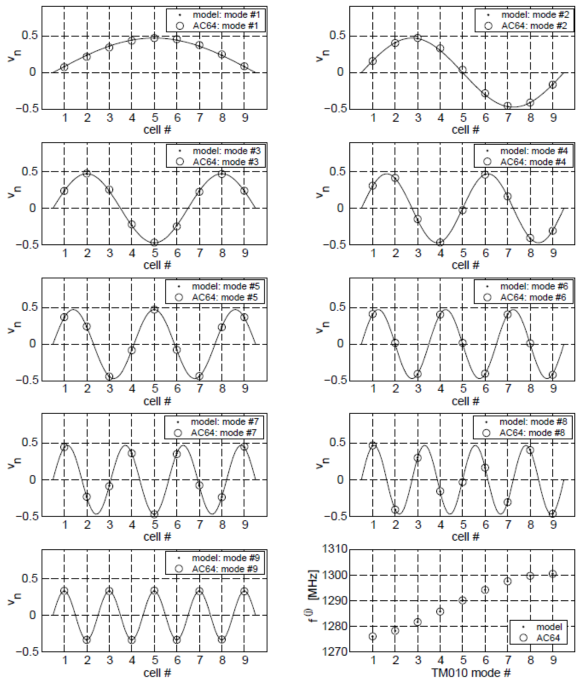
Cell-to-Cell Coupling



$$k_{cc} = \frac{\omega_\pi - \omega_0}{\frac{\omega_\pi + \omega_0}{2}}$$

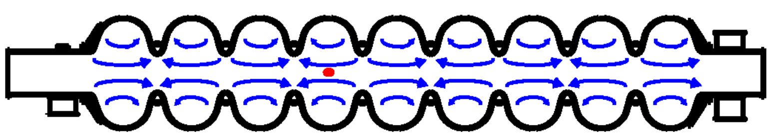
Coupling factor: $$k_{cc} = \frac{c}{\omega_0} \int_{S_i} \left(\vec{e} \times \vec{h} \right) \cdot \vec{u}_z ds$$

Multicell cavities



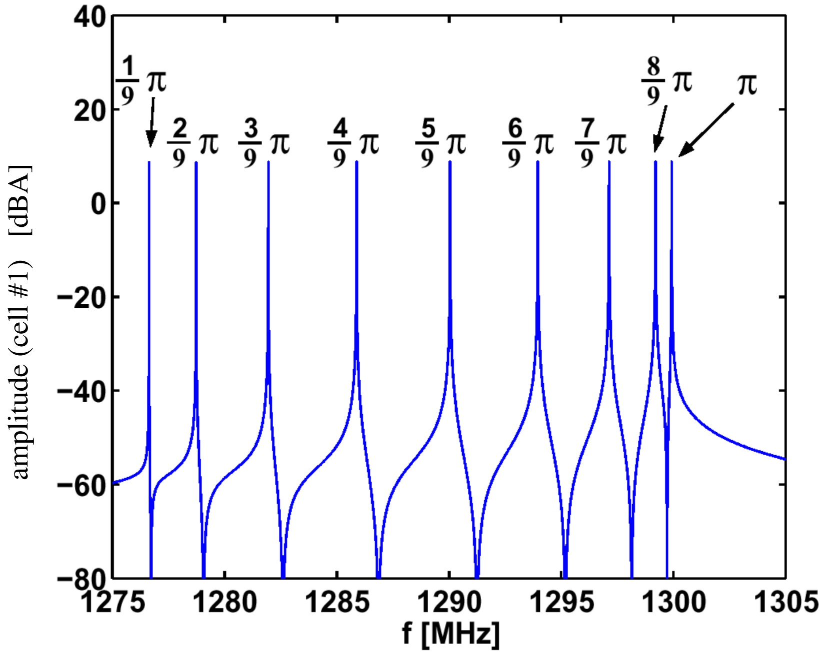
- Figure shows an example of calculated eigenmodes amplitudes in a 9-cell TESLA cavity compared to the measured amplitude profiles. Also shown are the calculated and measured eigenfrequencies.
- A longer cavity with more cells has more modes in the same frequency range, hence the reduction in frequency difference between adjacent modes. The number of cells is usually a result of the accelerating structure optimization.
- The accelerating mode for SC cavities is usually the π-mode, which has the highest frequency for electrically coupled structures.
- The same considerations are true for HOMs.

Accelerating π-mode:

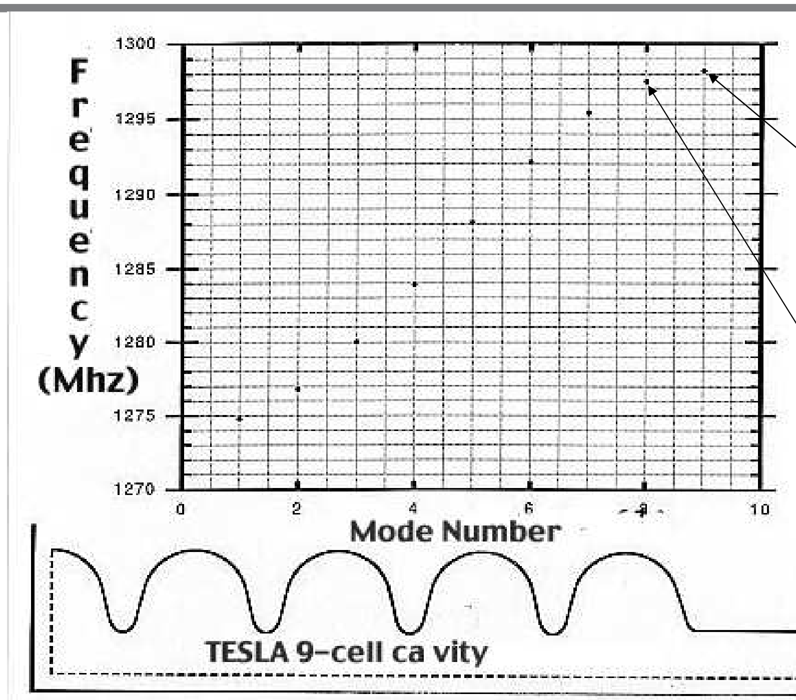


- cell-to-cell phase advance
- bunch takes ½ RF period pass cell
  -> energy gain in each cell!

Simulation Example:
TM010 Eigenmode-Spectrum of a 9-Cell Cavity



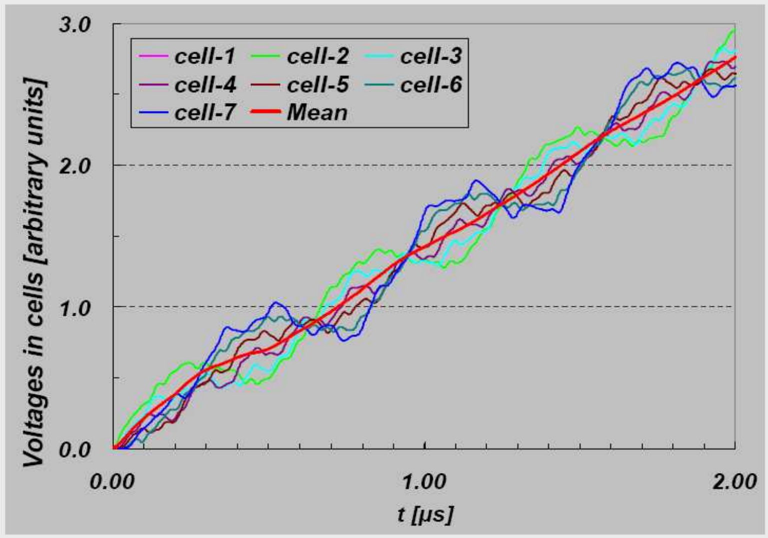
Dispersion Relation



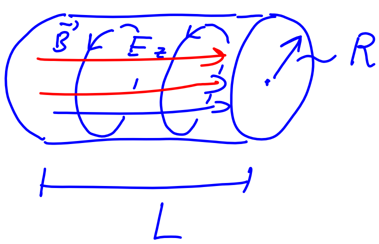
The working point. If it is too close to the neighbor point this neighbor mode can also be excited. To avoid this, more cell-to-cell coupling is needed: broader aperture.

Mode Beating during Cavity Filling

- **Modeling of the transient state (mode beating)**
  Example: 7-cells, k_{cc}=1.85%, Q_L=3.4 10^6



5.2.4 The pillbox cavity



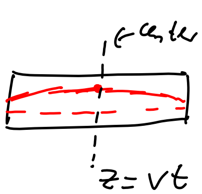
accelerating mode TM010

$$E_z = E_0 J_0\left(\frac{2.405\, r}{R}\right) e^{i\omega t}$$

$$H_\rho = -i E_0 \sqrt{\frac{\varepsilon_0}{\mu_0}} J_1\left(\frac{2.405\, r}{R}\right) e^{i\omega t}$$

$$\omega_{010} = \frac{2.405}{R} c$$, i.e. indep. of L

- Transit-time-factor:



$$T \equiv \frac{V_c}{E_0 \cdot L}$$ ← effective accelerating voltage; energy gain $\Delta E = q \cdot V_c$

← particle speed v

$$= \frac{\int_0^{L/2} E_0 \cos\left(\omega \frac{z}{v}\right) dz}{E_0 \, L/2} = \frac{\sin \xi}{\xi}$$

with $\xi = \frac{\omega}{v}\frac{L}{2}$

⇒ for $L = \beta \frac{\lambda}{2}$ (transit-time $= \frac{1}{2}$ RF period)
⇒ $T = 2/\pi < 1$

- Quality factor Q_0:

$$Q_0 = \omega \frac{\text{stored energy}}{\text{Power dissipated in walls}}$$

$$|E| = E_0 J_0\left(\frac{\omega}{c} r\right)$$

→ stored energy $= U = \frac{1}{2}\varepsilon_0 \int_0^{R}\int_0^{2\pi}\int_0^{L} E^2 \, d\varphi \, r\, dr\, dz$ } at $t=t_0$ with $E = E_{max}$ and $B=0$

$$= \frac{1}{2}\varepsilon_0 L 2\pi E_0^2 \int_0^R J_0^2\left(\frac{\omega}{c} r\right) r\, dr \qquad \frac{\omega}{c}R = 2.405 \ (1^{st} \text{ zero of } J_0)$$

$$= \frac{1}{2}\varepsilon_0 L 2\pi E_0^2 \left(\frac{c}{\omega}\right)^2 \int_0^{z_{01}=2.405} J_0^2(u)\, u\, du \qquad \text{with } u = \frac{\omega}{c} r$$

use

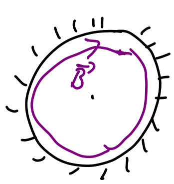
$$\int_0^{z_{01}} J_0^2(u)\, u\, du = \frac{1}{2}\Big(z_{01} \underbrace{J_1(z_{01})}_{0.52}\Big)^2$$

$$\Rightarrow U = \frac{1}{2}\varepsilon_0 \Big\{ \underbrace{L\, 2\pi \,\frac{1}{2}\left(\frac{c}{\omega}\right)^2\left(\frac{\omega}{c}R\right)^2}_{L\pi R^2 = Vol} \Big\} E_0^2 J_1^2(2.405)$$

$$= \frac{1}{2}\varepsilon_0 \underbrace{E_0^2 \cdot J_1^2(2.405)}_{\text{average field}^2 = \bar{E}^2,\ \text{since } E = E(r)} \cdot Vol$$

→ Power dissipated in walls:

$E_\parallel = 0$ at walls, but wall currents are induced by $B_\parallel(t)$

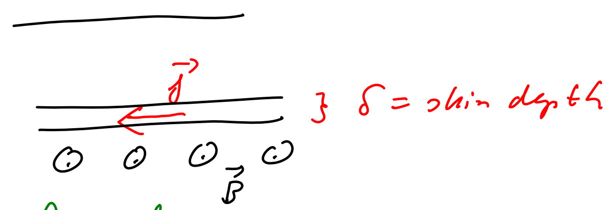


⇒ surface currents with skin depth: $\delta = \sqrt{\frac{2}{\mu_0 \omega \sigma}}$

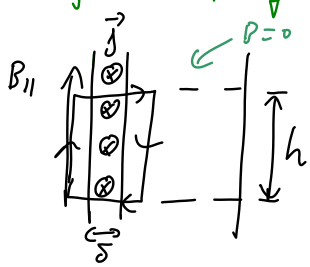
σ = conductivity

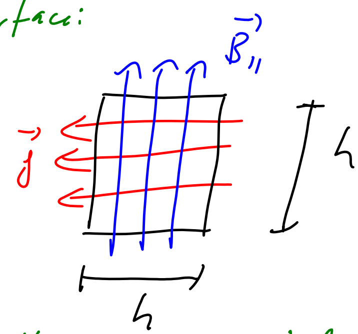
Example: copper: $\sigma = 5.96 \cdot 10^7 \frac{1}{\Omega m}$

⇒ $\delta = 3\,\mu m$ at $f = 0.5$ GHz



for small square of surface:





$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{inside path}}$$

current density

$$\Rightarrow \quad B_{\parallel} \cdot h = \mu_0 \, j \, h \, \delta \quad \Rightarrow \quad j = \frac{1}{\mu_0} \frac{B_{\parallel}}{\delta}$$

surface resistance:

$$\underline{\underline{R_s}} = \rho \frac{\text{length of conductor}}{\text{x-sectional area}} = \rho \frac{h}{h \, \delta} = \underline{\underline{\frac{1}{\sigma \delta}}}$$

(ρ ↑ resistivity $= \frac{1}{\sigma}$)

example: copper at 300 K: $f = 0.5$ GHz → $\underline{R_s} = \underline{5.7 \, m\Omega}$

⇒ dissipated power per surface area:

(← from time average (RF fields!) $\langle \cos^2 \rangle = \frac{1}{2}$)

$$\frac{P}{A} = \frac{\frac{1}{2} R_s I^2}{A} = \frac{1}{2} R_s \frac{(j \, h \, \delta)^2}{h^2}$$

$$\Rightarrow \quad \underline{\underline{\frac{P}{A}}} = \frac{1}{2} R_s \frac{1}{\mu_0^2} B_{\parallel}^2 = \underline{\underline{\frac{1}{2} R_s H_{\parallel}^2}}$$

⇒ for total power dissipated in walls, integrate P/A over entire surface of pillbox cavity:

with $|B_{\parallel}| = \frac{E_0}{c} J_1\left(\frac{\omega}{c} r\right)$

$$P_{tube} = \frac{1}{2} R_s \frac{1}{\mu_0^2} \int_A \frac{E_0^2}{c^2} J_1^2\left(\frac{\omega}{c} R\right) da$$

$$= \frac{1}{2} R_s \frac{\varepsilon_0}{\mu_0} E_0^2 J_1^2\left(\frac{\omega}{c} R\right)(2\pi R L)$$

$$P_{end\ walls} = 2 \cdot \frac{1}{2} R_s \frac{\varepsilon_0}{\mu_0} E_0^2 \int_0^{2\pi}\int_0^{R} J_1^2\left(\frac{\omega}{c} r\right) r\,dr\,d\varphi$$

two plates ↗

$z_{01} = \frac{\omega}{c} R$

$$= \frac{1}{2} R_s \frac{\varepsilon_0}{\mu_0} E_0^2 4\pi \left(\frac{c}{\omega}\right)^2 \int_0^{z_{01}} J_1^2(u)\, u\, du$$

with: $$\int_0^{z_{01}} J_1^2(u)\, u\, du = \frac{u^2}{2}\left(J_1^2(u) - \underbrace{J_0(u) J_2(u)}_{=0 \text{ at } u=0,\ u=z_{01}}\right)\Bigg|_0^{z_{01}}$$

$$\Rightarrow P_{end\ walls} = \frac{1}{2} R_s \frac{\varepsilon_0}{\mu_0} E_0^2 J_1^2\left(\frac{\omega}{c} R\right)(2\pi R L)\frac{R}{L}$$

$$\Rightarrow P_{walls} = P_{tube} + P_{end\ walls}$$

$$= \frac{1}{2} R_s \frac{\varepsilon_0}{\mu_0} E_0^2 J_1^2\left(\frac{\omega}{c} R\right) 2\pi R L \left(1 + \frac{R}{L}\right)$$

⇒ quality factor:

$$Q_0 = \omega \frac{U}{P_{walls}} = \frac{\mu_0 c\, 2.405}{2 R_s (1 + R/L)}$$

example: copper at 300K, $f = 0.5$ GHz, $L = \lambda/2$

$\Rightarrow Q \approx 30{,}000$

- geometry factor G

$$G = Q_0 \cdot R_s = \frac{\mu_0 c \cdot 2.405}{2(1+R/L)}$$

cavity radius $\propto \frac{1}{f}$
cavity length $\propto \frac{1}{f}$
$\Rightarrow$ G is independent of material properties and frequency; defined by shape only!

$\Rightarrow$ for pillbox cavity with $L = \frac{\lambda}{2}$:

$$R = \frac{2.405}{\omega} \cdot c \qquad L = \frac{\lambda}{2} = \frac{c}{\omega}\pi$$

gives: $G = \frac{\mu_0 c \, 2.405}{2\left(1+\frac{2.405}{\pi}\right)} = \underline{\underline{257\,\Omega}}$

- shunt impedance for $L = \lambda/2 \rightarrow T = \left(\frac{2}{\pi}\right)$

$$R_{sh} = \frac{V^2}{P_{walls}} = \frac{\left(\frac{2}{\pi}\right)^2 E_0^2 L^2}{\frac{1}{2} R_s \frac{\varepsilon_0}{\mu_0} E_0^2 J_1^2\left(\frac{\omega}{c}R\right) 2\pi R L \left(1+\frac{R}{L}\right)}$$

$$= \frac{4L}{\pi^3 R_s \frac{\varepsilon_0}{\mu_0} J_1^2\left(\frac{\omega}{c}R\right) R \left(1+\frac{R}{L}\right)}$$

- R/Q-factor for pill-box cavity with $L = \lambda/2$

$$\frac{R_{sh}}{Q_0} = \frac{4L \, 2 R_s (1+R/L)}{\pi^3 R_s \frac{\varepsilon_0}{\mu_0} J_1^2\left(\frac{\omega}{c}R\right) R (1+R/L) \mu_0 c \cdot 2.405}$$

$$\frac{L}{R} = \frac{\pi}{2.405}$$

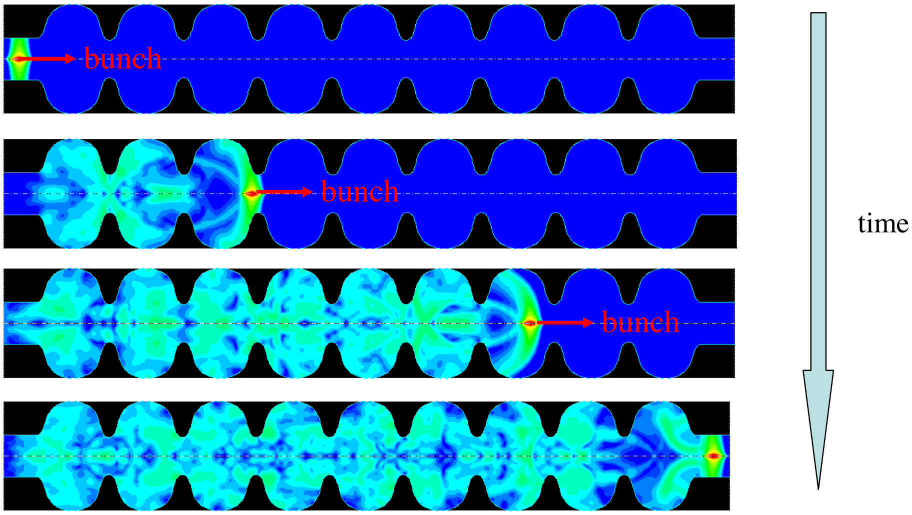
$$\Rightarrow \frac{R_{sh}}{Q_0} = \frac{8}{\pi^2 \varepsilon_0 J_1^2(2.405)\, c \cdot 2.405^2} = 196\,\Omega$$

i.e. indep. of R_s, f; defined by shape only

5.2.5 Higher-Order-Modes

- Higher order modes
  - Introduction: HOMs
  - HOM excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

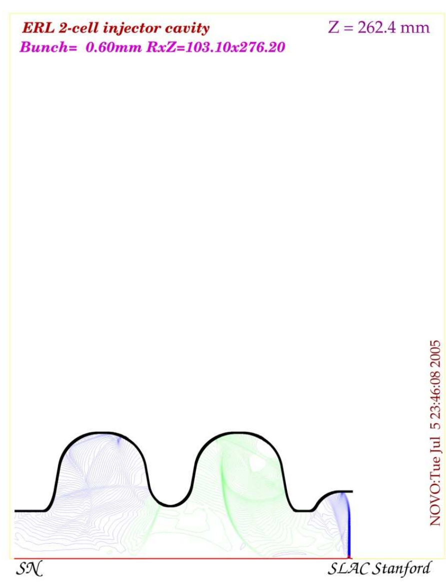
HOM Excitation by a Bunch



The bunched beam excites higher-order-modes (HOMs)
= wakefields = electromagnetic fields in the cavity.

Beam-Cavity Interaction

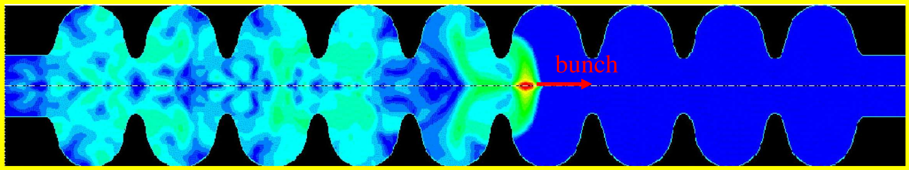
- Bunch traverses a cavity
- $\Rightarrow$ deposits electromagnetic energy, which is described as wakefields (time domain) or higher-order modes (HOMs, frequency domain)
- Subsequent bunches are affected by these fields and at high beam current one must consider instabilities



from S. Belomestnykh

Single Bunch Monopole Losses: Wake Potential of a Point-Charge

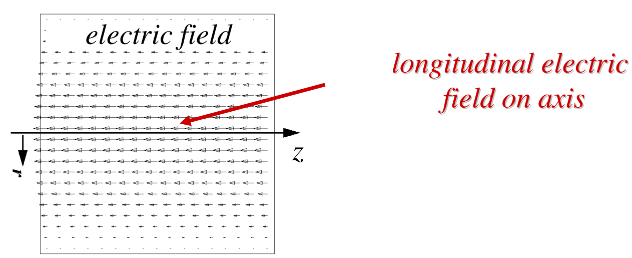
The beam excites higher-order-modes (HOMs) in a cavity:



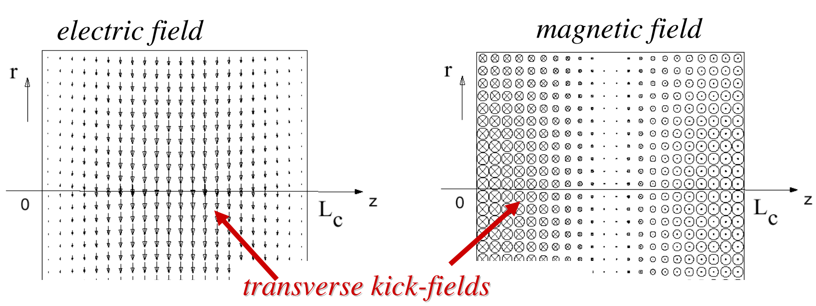
- When a charge passes through a cavity, it excites HOMs.
- If it passes exactly an axis, it will only excite monopole modes.
- For a point charge, the HOM excitation depends only on the bunch charge and the cavity shape.
- The excited field can be described by the wake potential.

Higher-Order-Modes (HOMs)

Monopole modes



Dipole modes, quadrupole modes,…



Monopole, Dipole and Quadrupole Modes…

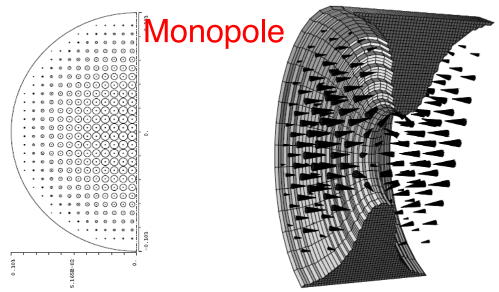


Figure 5: One mid-cell of a TESLA cavity. The electric field of the 1.3 GHz accelerating π-mode is shown. The left graph shows the electric field in a plane perpendicular to the cavity axis.

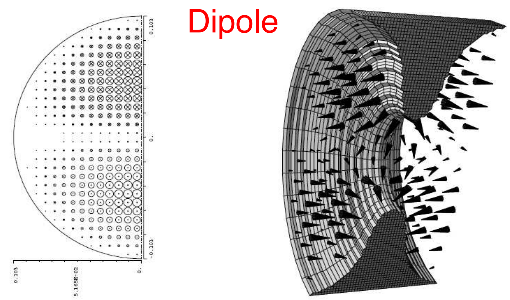


Figure 6: One mid-cell of a TESLA cavity. The electric field of the 1.79 GHz π-mode of the first dipole passband is shown. The left graph shows the electric field in a plane perpendicular to the cavity axis.

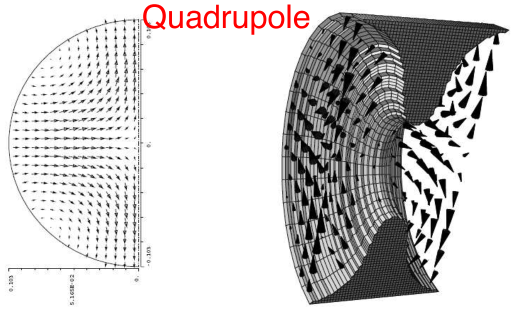


Figure 7: One mid-cell of a TESLA cavity. The electric field of the 2.32 GHz π-mode of the first quadrupole passband is shown. The left graph shows th electric field in a plane perpendicular to the cavity axis.

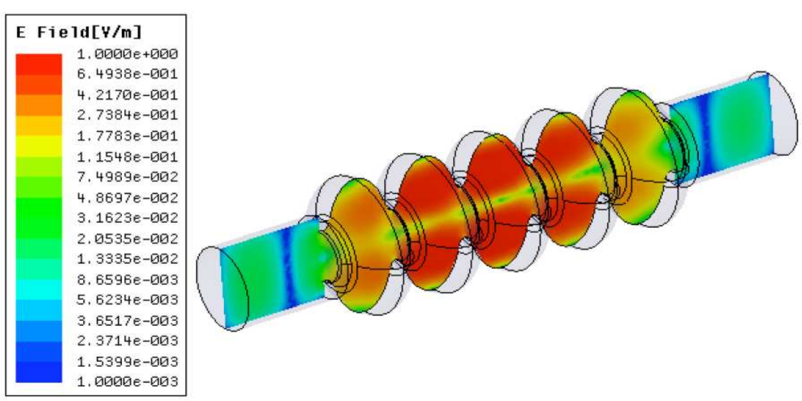
$$\widetilde{\boldsymbol{E}}(r,\phi,z) = \sum_m \Big(\widetilde{E_r^{(m)}}(r,z)\,\cos(m\,\phi)\;\;\boldsymbol{e_r} + \widetilde{E_\phi^{(m)}}(r,z)\,\sin(m\,\phi)\;\;\boldsymbol{e_\phi} + \widetilde{E_z^{(m)}}(r,z)\,\cos(m\,\phi)\;\;\boldsymbol{e_z} \Big)$$

$$\widetilde{\boldsymbol{B}}(r,\phi,z) = \sum_m \Big(\widetilde{B_r^{(m)}}(r,z)\,\sin(m\,\phi)\;\;\boldsymbol{e_r} + \widetilde{B_\phi^{(m)}}(r,z)\,\cos(m\,\phi)\;\;\boldsymbol{e_\phi} + \widetilde{B_z^{(m)}}(r,z)\,\sin(m\,\phi)\;\;\boldsymbol{e_z} \Big).$$

from R. Wanzenberg

Methods of HOM Calculations: Frequency Domain

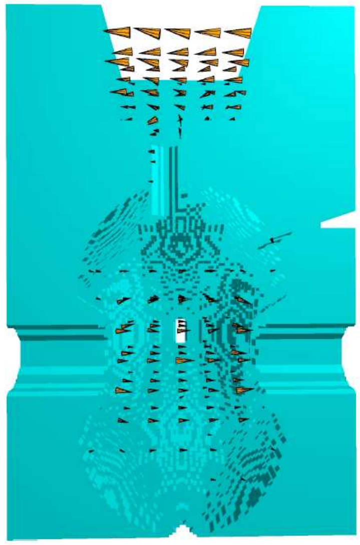
Complex eigenvalue solution (becoming available, SLAC codes, ANSYS beta, HFSS) gives real and imaginary parts of impedance directly, hence R and Q.



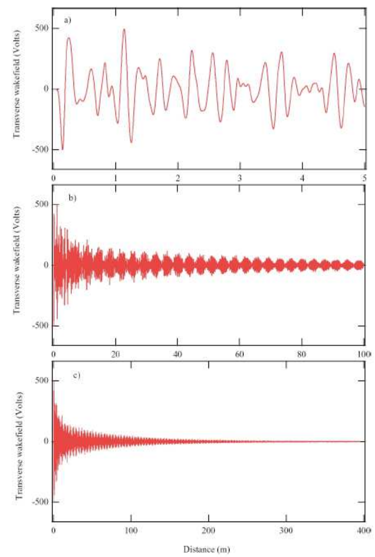
HFSS 3D complex Eigenvalue solution, 5-cell cavity with enlarged beam-pipes.

Time-Domain Method (I)

Time domain (FFT) method (developed at SLAC, widely used, ABCI, MAFIA etc.)



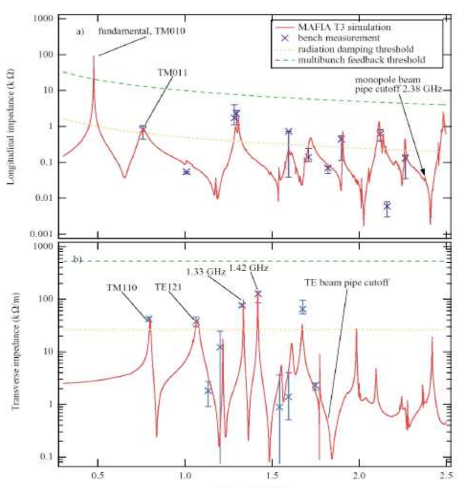
3D MAFIA model of PEP-II cavity.



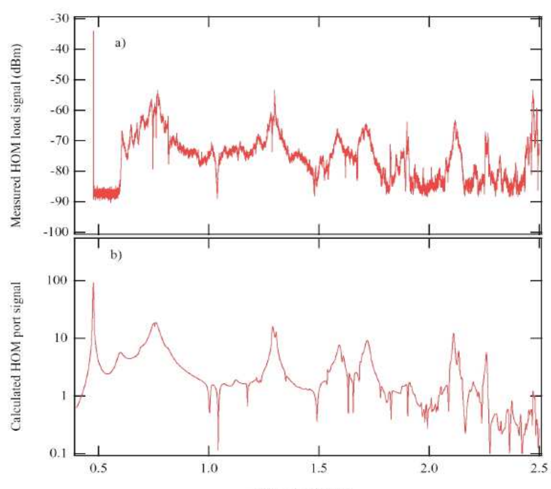
Short-, medium- and long-range wakes*.

*(2000) Physical Review Special Topics – Accelerators and Beams, Volume 3, 102001

Time-Domain Method (II)



Calculation vs bead-pull measurements.



Measured vs calculated HOM spectrum.

Method uses open boundaries on ports. FFT of long-range wake gives broad-band impedance spectrum in one run. Works best for strong coupling ($\beta >> 1$). Frequency resolution set by wake length, max frequency set by mesh size (typ. ~10 GHz).

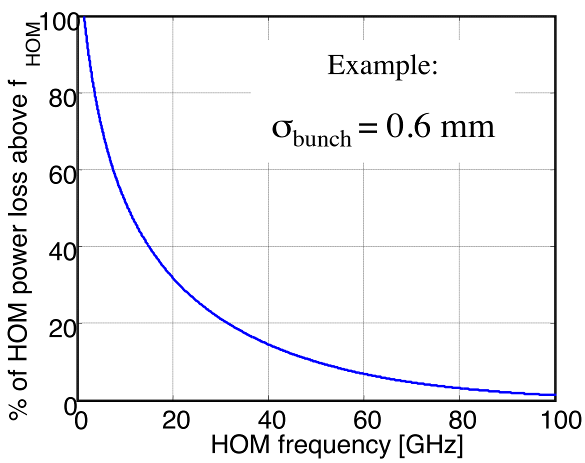
HOMs

- Higher order modes
  - Introduction: HOMs
  - HOM excitation by a beam
  - HOM damping schemes
  - HOM damping examples and results

HOM Excitation

The excited HOM power of a single bunch depends on:

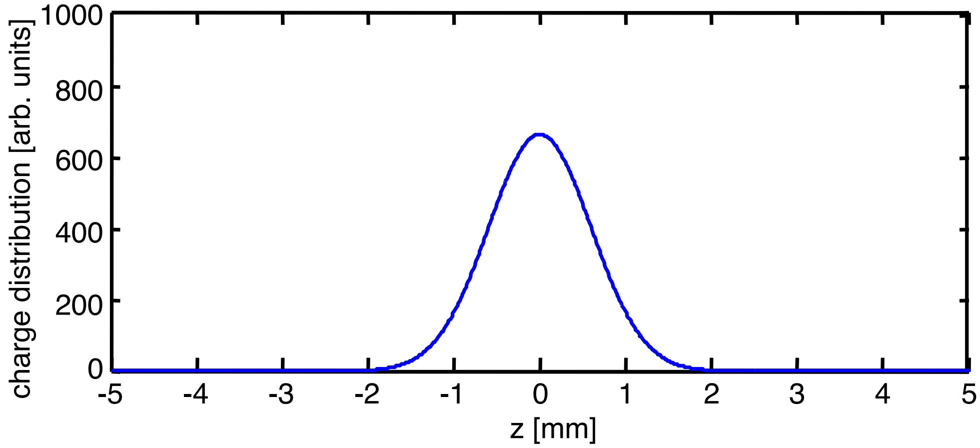
- the HOMs of the cavity (i.e. their shunt impedance),
- the bunch charge ($P_{HOM} \propto q_b^2$),
- the bunch length (i.e. the spectrum of a bunch).



⇒ Short bunches excite very high frequency modes!

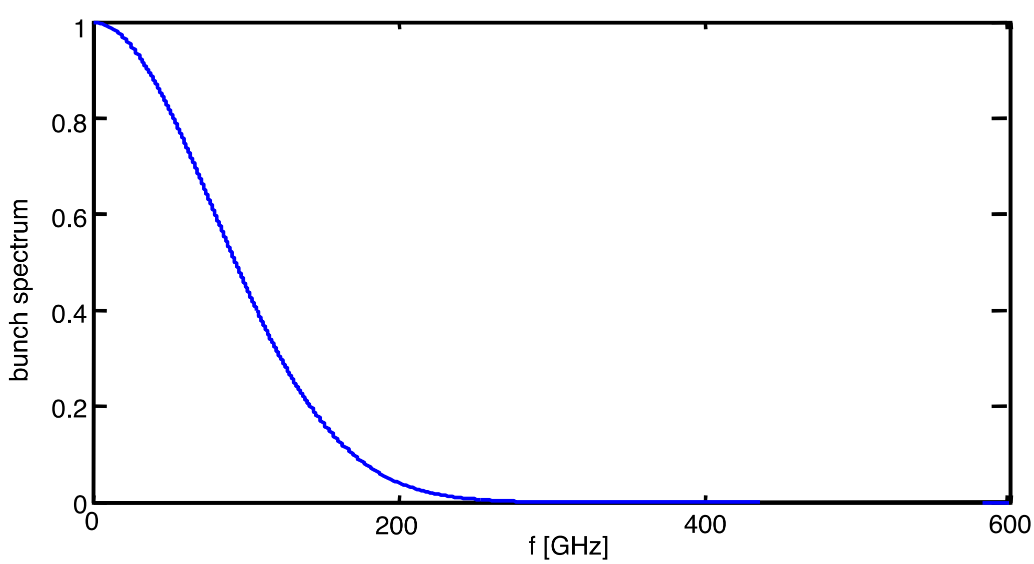
Single Bunch Monopole Losses: The Bunch

Longitudinal charge distribution for a 600 μm bunch:



Single Bunch Monopole Losses: The Bunch Spectrum

Spectrum of a 600 μm bunch:



Beam-cavity interaction: Wave Function

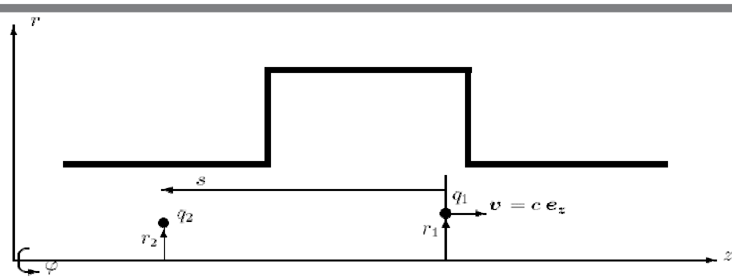
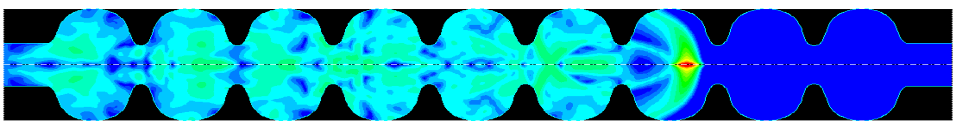


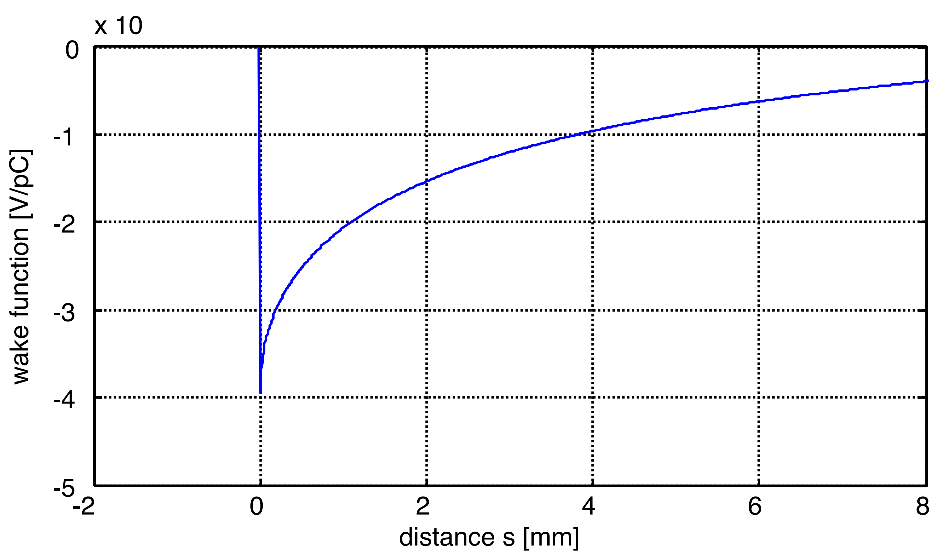
Figure 8: A point charge q_1 traversing a cavity with an offset r_1 followed by a test charge q_2 with offset r_2 .

Lorentz-Forces on test charge: $$\boldsymbol{F} = \frac{d\boldsymbol{p}}{dt} = q_2\,(\boldsymbol{E} + c\,\boldsymbol{e}_z \times \boldsymbol{B}).$$

The integrated field seen by a test particle traveling on the same path at a constant distance *s* behind a point charge *q* is the longitudinal wake (Green) function *w(s)*.

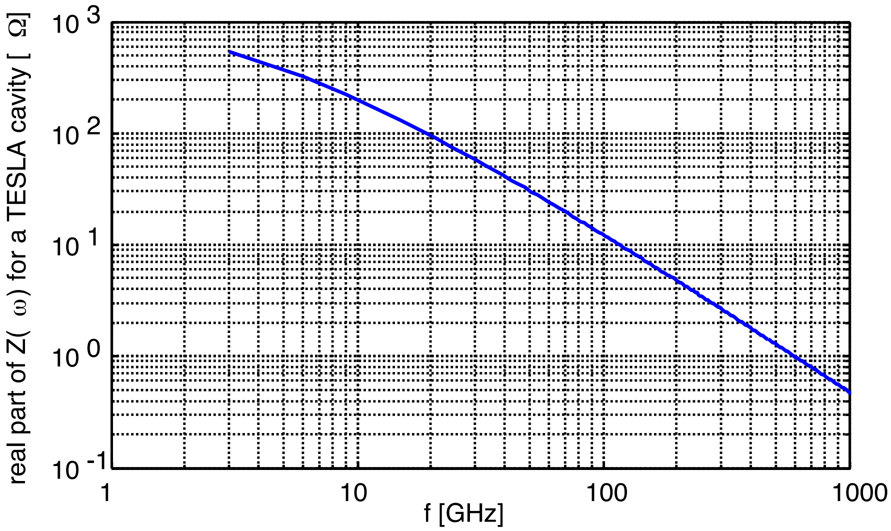


Single Bunch Monopole Losses: Wake Function of a Point Charge after a TESLA Cavity

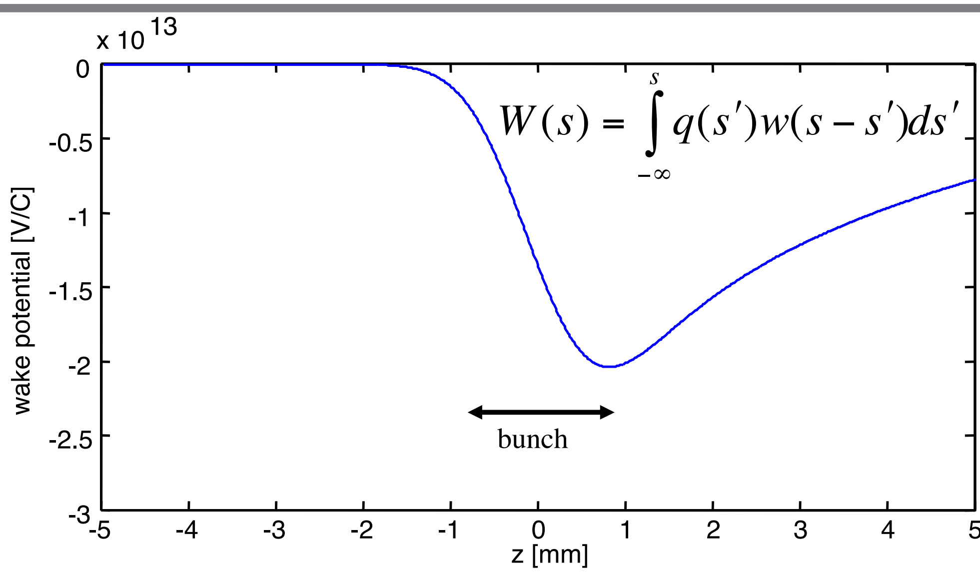


Single Bunch Monopole Losses: Wake Potential of a Point Charge after a TESLA Cavity

The fft of the wake function gives the cavity impedance Z(ω):



Single Bunch Monopole Losses: Wake Potential of a Bunch after a TESLA Cavity



$$W(s) = \int_{-\infty}^{s} q(s')w(s-s')ds'$$

The wake potential *W* is a convolution of the linear bunch charge density distribution *q(s)* and the wake function *w*

Single Bunch Monopole Losses: Loss Factor

Once the longitudinal wake potential is known, the longitudinal loss factor, which tells us how much electromagnetic energy a bunch leaves behind in a structure can be defined as:

$$k = \frac{\Delta U}{q^2} \qquad k_{||} = \int_{-\infty}^{\infty} q(s) W(s) ds$$

Average power loss:

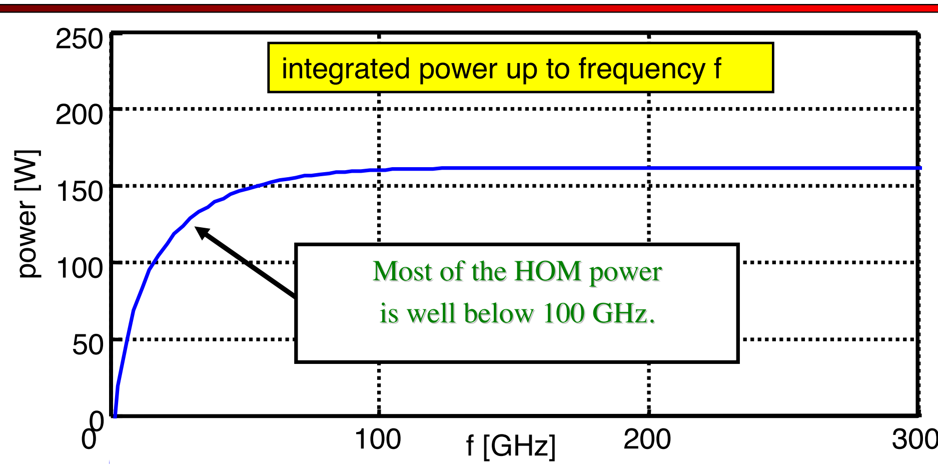
$$P_{||} = k_{||} Q_{bunch} I_{beam}$$

- This is the total energy lost by a bunch divided by the time separation of two consecutive bunches.
- This does not include any interaction between bunches (i.e. resonant mode excitation)!!!

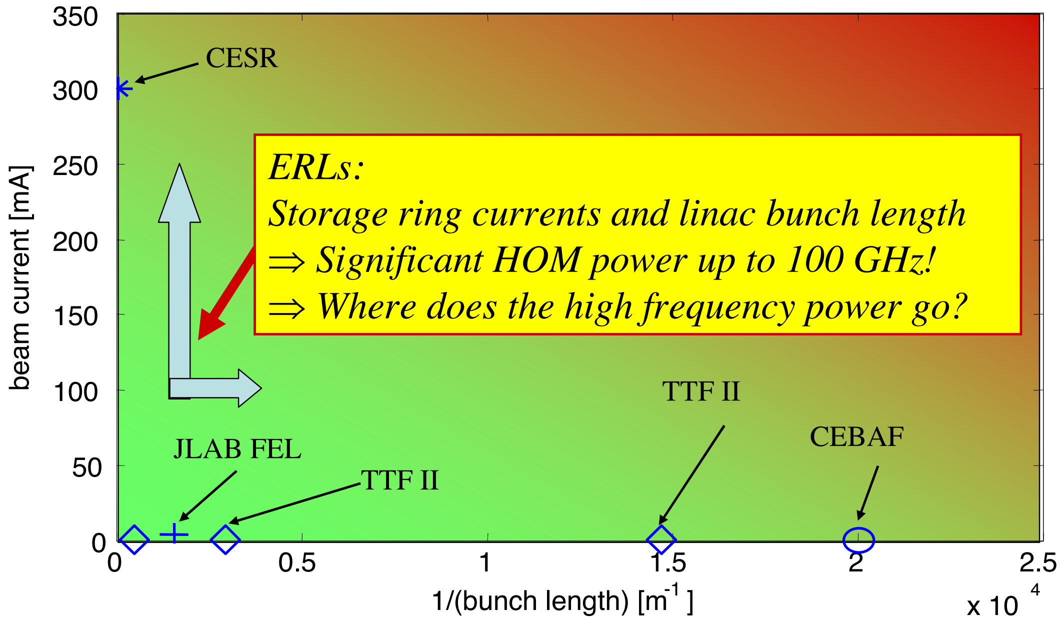
Single Bunch Monopole Losses: HOM Power Frequency Distribution

The frequency distribution of the HOM losses is determined by the bunch spectrum *and* the cavity impedance Z(ω):

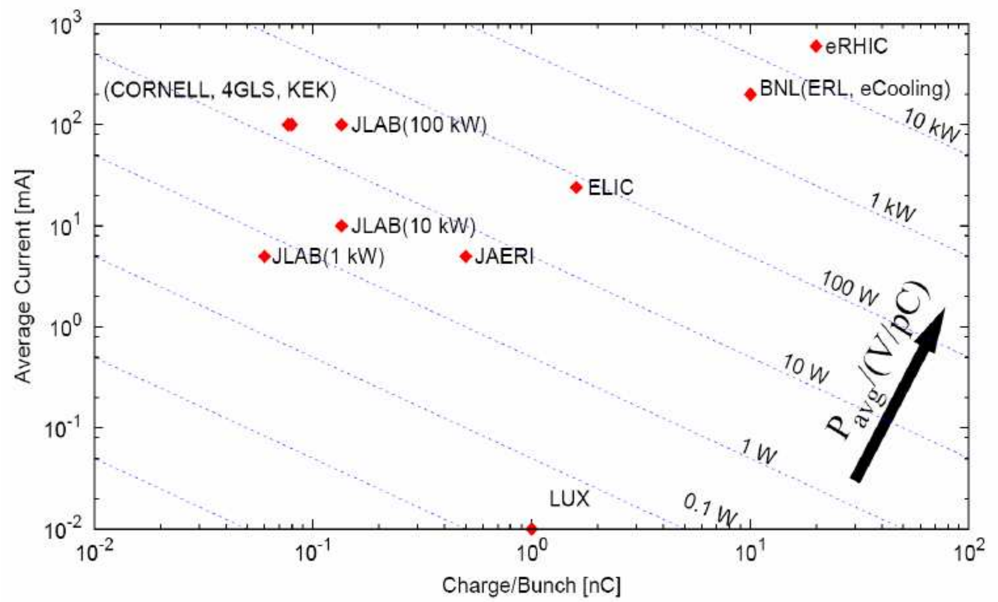
$$P(\omega) \propto Z(\omega)\left[\tilde{q}(\omega)\right]^2$$



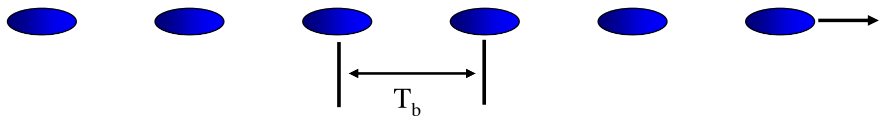
High current and short bunches



Average HOM Power Examples



Bunch Trains



- The HOMs excited by a bunch are decaying due to losses,
- but: still significant field present in the cavity when the next bunch enters the cavity!
- ⇒ Resonant excitation of a HOM, if

$$f_{HOM} \approx N \frac{1}{T_b}$$

HOM Excitation

The excited HOM power of a bunch train depends on:

- the HOM losses of a single bunch,
- the beam harmonic frequencies and the HOM frequencies (resonant excitation is possible!),
- the bunch charge and the beam current ($P_{HOM} \propto QI$),
- and the external quality factor, Q_{ext} of the modes. Lower Q_{ext} means less energy deposited by the beam:

$$P_{HOM} \propto Q_{ext}$$

Bunch Trains and HOM Power

In *average* the total HOM losses per cavity are given by the single bunch losses (77 pC bunch charge, 2.6 GHz bunch repetition rate, σ_b= 600 μm):

$$P_{||} = k_{||} Q_{bunch} I_{beam} = 10.4\,\mathrm{V/pC} \cdot 77\,\mathrm{pC} \cdot 0.2\,\mathrm{A} = 160\,\mathrm{W}$$

But: If a monopole mode is excited on resonance, the loss for this mode can be much higher:

$$P = \left(\frac{R}{Q}\right) Q I_{beam}^2$$

Example: To stay below 200 W:

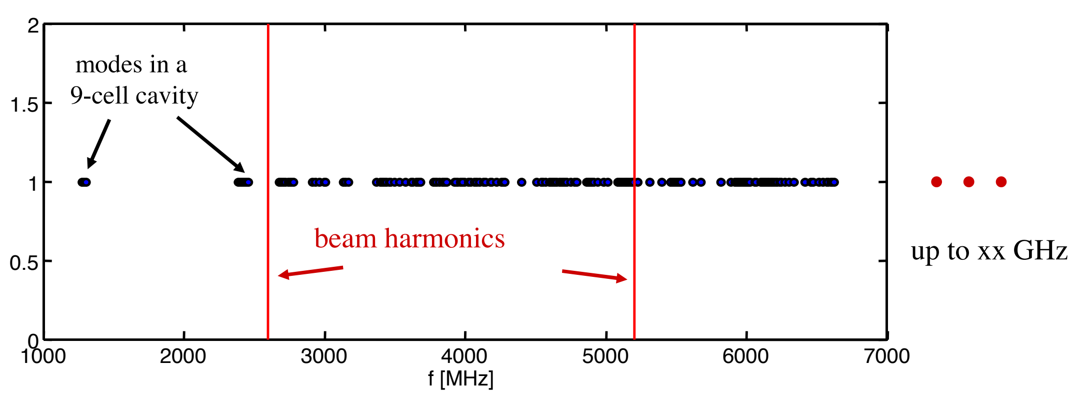
- achieve (R/Q)Q < 5000,
- or avoid resonant excitation of the mode.

Bunch Trains and Beam Harmonics

Example: Cornell ERL:

$$f_{HOM} = N \cdot 1.3\,\text{GHz in the injector}$$
$$f_{HOM} = N \cdot 2.6\,\text{GHz in the main linac}$$

… so most of the monopole modes in the ERL will not be excited resonantly.



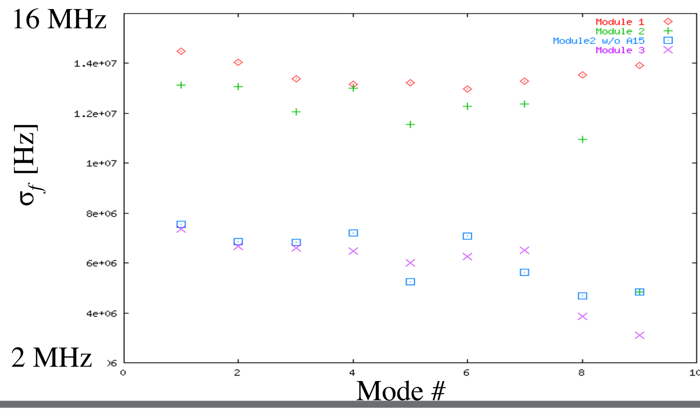
Bunch Trains: HOM Frequencies Spread

Can one design the HOM frequencies such, that non of the modes are excited resonantly?

- The higher the frequency, the more sensitive is the frequency of a HOM to small perturbations in the cavity shape:

  Simple approximation: $\frac{\Delta f_{HOM}}{f_{HOM}} = const.$

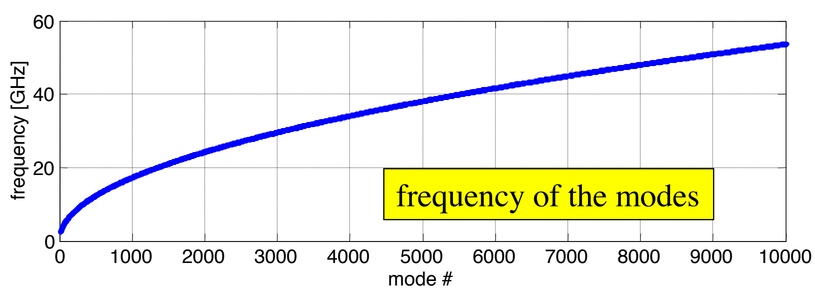
- How large is "const"? Example: 2.4 GHz modes at TTF

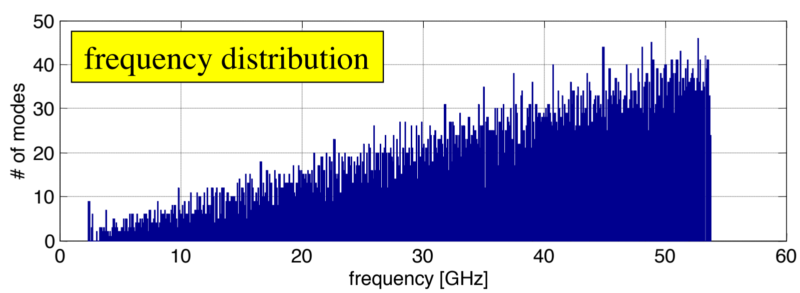


σ_f = 10 MHz
$\Rightarrow$ const = 0.4 %

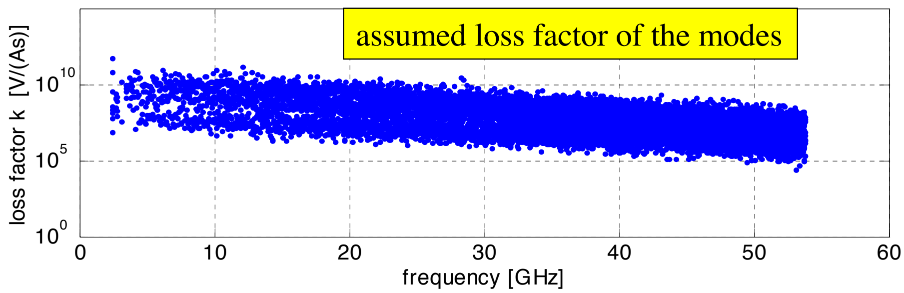
i.e. *σ_f = 20 MHz at 5.2 GHz*
σ_f = 31 MHz at 7.8 GHz
σ_f = 42 MHz at 10.4 GHz
…

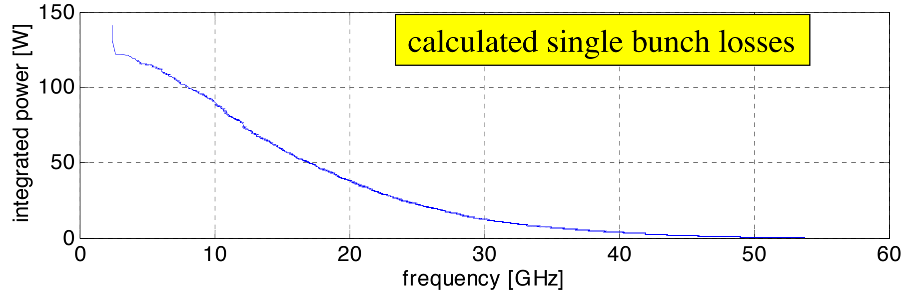
Bunch Trains:
A Simple Model: 10000 Monopoles with random f's



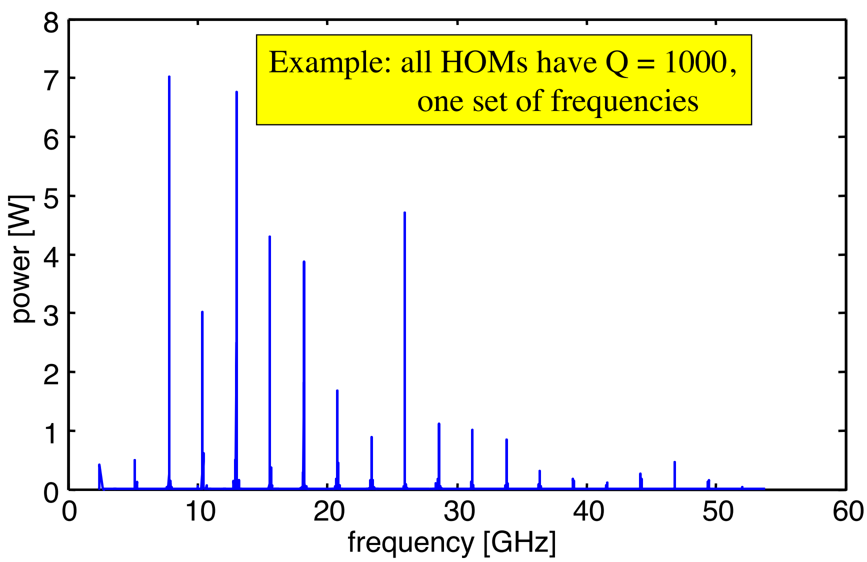


Bunch Trains:
A Simple Model: 10000 Monopoles with random f's

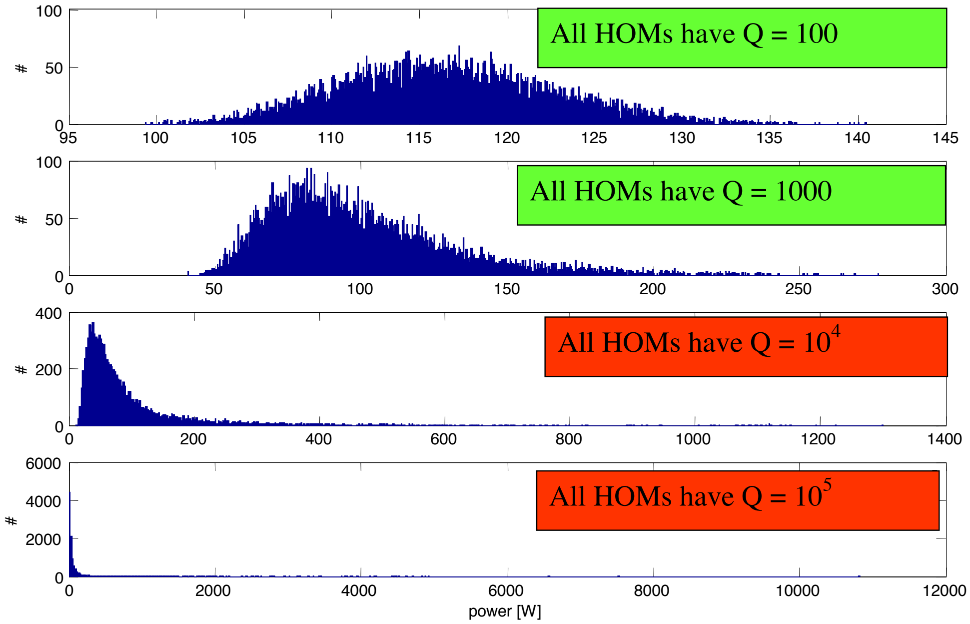




Bunch Trains:
A Simple Model: 10000 Monopoles with random f's



A Simple Model: 1000 Monopoles with random f's
Total HOM Monopole Power for random Sets of Frequencies



Higher-Order-Modes (HOMs)

Parasitic modes excited by the accelerated beam may lead to:

- degradation of the beam quality (transverse emittance growth due to dipole modes, BBU, energy spread),
- additional cryo-losses (wall losses, heating of cables and feedthroughs), mostly due to monopole modes.

⇒ ***Requirements on the external quality factor, Q_{ext} of the modes.***

Without additional damping the HOMs can have very high quality factors ($Q>10^{10}$)!